

# RECENT DEVELOPMENTS IN THE WELDING OF LIGHT METALS AND ALLOYS

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**T**HE popularity and increase in use of any metal and its alloys in industry depend largely on their weldability. The post-war development of inert gas shielded arc welding processes, which made it possible to obtain consistently and easily, reliable and good welds in the difficult-to-weld light metals and alloys contributed a great deal to the recent phenomenal increase in the use of these materials. This situation has greatly been helped by the latest development of readily weldable alloys, especially aluminium-magnesium alloys, which are cold worked and therefore do not suffer the same loss in properties as experienced with some of the other precipitation hardening alloys.

## Gas welding, brazing and metal arc welding

In the past, most of the light metals and alloys especially aluminium and magnesium were welded by the oxy-acetylene gas welding process and to a lesser extent by the metal arc process using covered electrodes. However, as these metals easily develop refractory oxides whose melting points are, in some cases more than three times those of the parent materials it was found necessary to use chemically reactive fluxes containing chlorides and fluorides of lithium and potassium to dissolve the oxides before welding could be achieved.

Although the use of chemically reactive fluxes resulted in satisfactory welds, it imposed restrictions on the joint design. For, the corrosive fluxes had to be scrupulously removed after welding was completed; otherwise the weld area would corrode in about a month's time. Certain joint designs such as fillet and lap welds were ruled out as it was difficult, if not impossible, to remove all the flux entrapped in the joints.

Brazing using alloys of a lower melting point than the parent material and a suitable flux was found to be a solution to this problem because the brazing material could flow in and completely fill up all the gaps in the joint. Nevertheless, the time consuming

and costly post-weld flux removing operations made this process also equally difficult and uneconomical.

Metal arc welding with covered electrodes was used to a still lesser extent because welding required a lot of skill on the part of the operator and the slag formed from the flux covering, which was equally corrosive, had to be thoroughly cleaned and thereby imposed the same restrictions on joint design as in gas welding.

To a large extent, therefore, resistance welding was used, mainly, in the aircraft industry, for welding these light alloys.

## Resistance welding

Resistance welding uses the heat produced by the passage of a high current through two pieces of metal to be joined. Due to the resistance at the interface this passage of current raises the temperature at the joint to the plastic range. At this stage, requisite pressure is applied to effect a homogeneous weld.

Light metals, especially aluminium, are good conductors of heat and electricity. Besides, as stated earlier, they produce a skin of oxide on the surface which is difficult to clean. The heat produced in watt-seconds by the passage of a current is equal to  $I^2RT$  where  $I$  is the current,  $R$  the resistance and  $T$  the time in the seconds for which the current flows. It is thus apparent that to get consistently good results on these materials by resistance welding, it is necessary to reduce heat losses to a minimum by keeping the current as high as possible, limiting the duration of its passage to the minimum and ensuring that the resistance  $R$  at the interface is as constant as possible.

In fact in resistance welding of aluminium very high currents are allowed to pass for a few cycles, say, 3 to 5 or  $\frac{1}{10}$ th to  $\frac{1}{100}$ th of a second. To produce these very high preset currents consistently and accurately without imposing corresponding high peak primary loads which would cause troublesome electrical disturbances, special electrical machinery is required. Resistance welding equipment for these light alloys, are therefore normally of the capacity, induction or battery storage type with synchronous timing controls. The latter ensure that for each operation the current is switched on and off at the same phase angle of the

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primary voltage wave; otherwise the first and the last cycles of the current wave get distorted in an unpredictable manner depending on the exact point on the voltage curve the current was switched on. As the weld is completed in 3 to 5 cycles, distortion of two of these cycles in an unpredictable manner will obviously mean welds of unpredictable quality and consistency.

Further, to ensure that the resistance at the interface is appreciably constant, it is necessary to pickle or clean the surfaces of these alloys prior to welding using chemical reagents such as trisodium phosphate detergents.

Resistance welding can be sub-divided into many branches the most important of which are spot, butt, flash butt and seam welding. Spot welding, as the name implies, is welding in small spots. Butt welding is done by holding together two abutting edges under pressure, passing the welding current so that the edges get heated to their plastic range and then applying further pressure till upsetting and welding take place. Flash welding differs from butt welding in that the edges are brought together after the current is switched on so that flashing takes place. The edges are heated by this flashing and a final pressure is applied to fuse the two edges. Seam welding is done by passing a current through a single or two rotating wheel-type electrodes through edges which are lapped. The current and pressure are interrupted as the wheels rotate over the seam resulting in a continuous longitudinal weld.

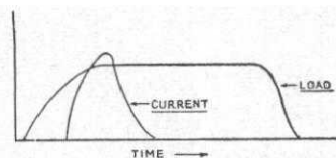
Latest developments in resistance welding of light metals have been confined to improvements in power sources and controls for welding variables.

In the old storage type of welders a sample or dual load cycle of pressure was employed (see Figs. 1 and 1A) but no current controls were available. The current rose and collapsed at a very steep angle. The heat cycle used to follow suit. The sudden heating of the weld area and consequent uneven heating resulted sometimes in the burning or splashing of the weld metal. The steep decay of current resulted in sudden chilling, and very rapid solidification of the metal and gave rise to cracks or porosity especially in the heat treatable alloys of aluminium whose plastic ranges are narrow.

Where the power demand is of no consequence the recent tendency has been to go back to the single phase A.C. resistance welders with programme, slope or slope-taper controls. Even in A.C. welding the peak currents occur every  $1/4$  cycle i.e. in .005 secs (see Fig. 2). This constitutes a steep rise and fall and suffers from the same limitations as imposed by simple storage type machines. Consequently, some special form of controls was found necessary.

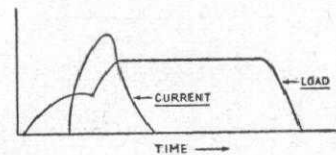
First, programme control was introduced to combat the tendency to crack. In this control the welding current cycles were followed by a few lower current cycles for post-heating and keeping the weld area in a plastic condition for a longer period, so that forging pressure could effectively eliminate the tendency to cracking and porosity (see Fig. 2A).

Fig. 1.



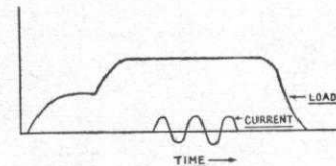
SIMPLE LOAD CYCLE  
(STORAGE TYPE)

Fig. 1A.



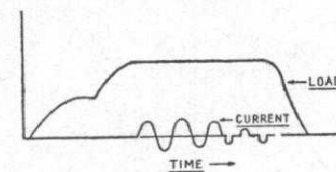
DUAL LOAD CYCLE  
(STORAGE TYPE)

Fig. 2.



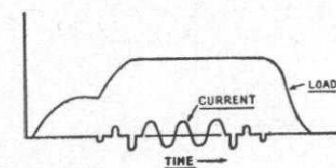
SIMPLE CONTROL  
(A.C. SINGLE PHASE)

Fig. 2A.



PROGRAMME CONTROL  
(A.C. SINGLE PHASE)

Fig. 3.



SLOPE-IN-TAPER CONTROL  
(A.C. SINGLE PHASE)

Next, the "slope-in" control was introduced to eliminate the tendency for splashing, by passing a few cycles of low current gradually increasing in intensity, before welding current commenced flowing so that the material would be preheated.

This control was followed by a combination of both and was called the "slope taper" or "slope-in/slope-out" control (see Fig. 3) which effectively eliminated the tendency to splash as well as crack.

Further modifications were made in the application of pressure. Instead of the simple or dual cycle, the pressure or load also followed a definite pattern.

As shown in Fig. 4 an initial high pressure to "squeeze" and flatten out any surface irregularities was followed by a reduced pressure during welding to increase the interface resistance and thus help increase the heat produced. This was followed by another period of high pressure for forging.

Fig. 4 shows the complete "preheat/weld/post-heat" current control with appropriate cool-off periods during this cycle of loading. The figure also represents the approximate relationship between the load and current cycles on the time axis. Fig. 5 shows the "slope-in/slope-out (taper)" control.

Fig. 4.

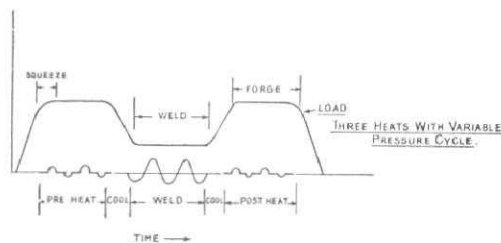


Fig. 5.

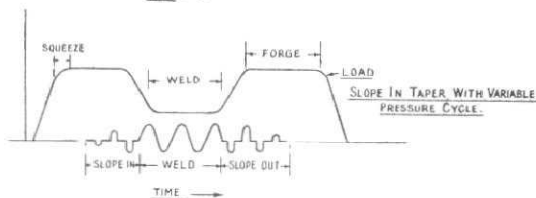


Fig. 6.

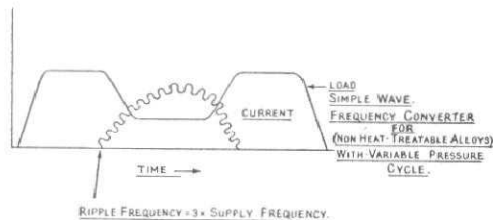
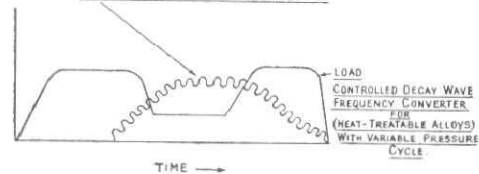


Fig. 7.



It will be appreciated from the foregoing that the controls required for successful welding of aluminium alloys especially of the heat treatable variety are very complicated indeed and are usually achieved by appropriate electronic means.

A still later development is the frequency converter, 3-phase, A.C. resistance welders. In these machines all the 3 phases of an A.C. supply are made to pass through a transformer which has a single secondary winding. The A.C. lines are connected to the 3-phase transformer windings through inversely connected ignitrons in pairs. By suitable controls the forward ignitrons are allowed to pass the first cycle of current followed by the reverse ignitrons and by timing this process it is possible to energise the welding transformer secondaries with a current of low frequency, say, 12 per sec. or lower. These cycles have superimposed on them a ripple, the frequency of which is thrice the supply frequency; for instance, 150 cycles if the supply is at 50 cycles.

For welding aluminium and its non-heat treatable alloys a simple wave form as shown in Fig. 6 is used but for heat treatable alloys, a controlled decay wave as shown in Fig. 7 is employed. It will be observed from the figures that although the third harmonic ripple of the 50-cycle frequency is present, the current never touches zero but rises steadily and decays in

a controlled manner. This current wave form is therefore eminently suitable for welding aluminium and even its heat treatable alloys.

Modern practice is to favour "slope-in/taper" controlled single phase A.C. transformers for welding thin sheets of aluminium if power problems are not important and to go in for the costlier 3-phase frequency converters for thicker sections.

### Inert gas shielded arc processes

The inert gas shielded arc processes are post-war developments which have added remarkable impetus to the use of aluminium, magnesium and their alloys because they provide an easy and reliable method for joining these materials.

The outstanding feature of the inert gas shielded arc welding processes is the complete absence of fluxes. This is possible because the action of the arc under proper conditions removes the oxide film already present and the shielding inert gas prevents its re-formation on the molten metal. Thus joints welded by inert gas are have better appearance, require no post-weld flux removal and usually require little or no finishing unless required flush. They also have sounder structures than welds normally made by other processes. Further, a high production rate is possible, the welding speed being 2 to 3 times faster than for steel of a similar thickness.

### Tungsten inert gas process

The tungsten inert gas process hereinafter referred to as TIG process was the first one developed. In this process an arc is struck between a practically non-consumable tungsten electrode and the job to be welded. The arc is surrounded by an inert gas such as argon or helium. The arc is used as heat source to melt the parent material to be welded. A filler metal, if required, is added additionally into the molten pool as in gas welding.

Early experiments using D.C. for light alloys showed that while positive polarity was required for disrupting the oxide films present on them, it caused overheating of the electrode which rapidly melted and disintegrated.

Next A.C. was tried as the power source; this also was found unsuitable because the positive half cycles so essential for the disruption of oxides were getting suppressed due to rectification. This rectification is inherent when an alternating current arc is struck between two dissimilar metals. To eliminate this inherent rectification a D.C. suppressor was developed. This consists of a bank of A.C. electrolytic condensers (usually of about 33,000 MFD in capacity for 300 amps welding current) which is connected in series in the welding circuit. It was observed that this device enabled perfect welds to be made on light alloys by TIG welding.

Another device required to ensure easy striking of the arc and stability in welding is the high frequency unit. This unit merely superimposes an HF current,



about 50 kilo cycles in frequency, over the welding current at a voltage of about 3,000 and helps to initiate the arc even before the tungsten electrode touches the work.

This high frequency unit however is likely to interfere with radio and television reception and has in more recent years been superseded by a surge injector.

The surge injector controls an arc starter which produces sparks of high frequency high voltage to start the arc and as soon as the arc is struck a relay reconnects the circuits so that the surge injector produces a surge voltage of about 300 every time the current is passing through zero after the negative half cycle. This enables the arc to be restruck without any delay during the positive half cycles and thus helps to stabilise the arc. The use of this device enables transformers of a low open circuit voltage, say, 50 volts to be employed. With the HF unit described before, for welding aluminium and magnesium alloys by TIG process, an open circuit voltage of 90 or 100 is required.

Tungsten electrodes which are comparatively costly get contaminated if an arc is started by the usual method of jabbing or striking it on the job to be welded. Therefore the use of HF unit or surge injector with an A.C. or D.C. power source is imperative so that an arc can be established by the ionisation created by the passage of HF sparks even when the electrode is, say, 1/8" away from the work piece.

The use of 1 to 2% zirconia or thoria in tungsten has been found to help initiation and maintenance of the arc and nowadays pure tungsten electrodes are seldom used.

Given in Tables I and IA are the typical welding conditions for manual TIG welding of aluminium.

To summarise, to weld light alloys by TIG process, an A.C. power source, a D.C. suppressor unit and a high frequency or surge injector unit are required besides the welding torch and argon or helium gas. Argon is preferred to helium because of its ready availability and its better arc characteristics. Further an arc struck in argon has better oxide scavenging properties and, being a heavier gas, the flow required to get effective shielding is very much less than that for helium.

### Strength of tungsten inert gas arc welded aluminium and its alloys

Strength of any particular welded joint will depend on several factors including the skill of the welder and the size of the pieces being joined. The welder's skill influences the quality of the weld and this as well as the size of the weld required affect the amount of heat put into an assembly and consequently the extent of annealing and weakening of the parent material. Thus when high quality joints are a critical requirement, the weld stresses should preferably be established and

TABLE I  
*Tungsten inert gas welding flat butt welds without backing.*

Thickness in	No. of passes	Edge preparation	Root opening in	Dia. of cup in	Dia. of electrode in	Current amps	Arc travel speed in/min	Dia. of filler in	Argon flow cft/hr
1/32	1	30° flange		3/8	1/16	30	18	—	8
		Recommended only for special applications							
3/64	1	(a)		3/8	3/32	75	18	3/32	10
		Recommended only for special applications							
1/16	1	(a)		3/8	3/32	90	13	3/32	12-14
5/64	1	(a)		3/8	3/32	115	12	1/8	12-14
3/32	1	(a)		3/8-1/2	1/8	135	12	1/8	12-14
1/8	1	(a)		3/8-1/2	1/8	160	12	1/8	12-14
	2 (rev)								
3/16	1	(b)	0-3/32	1/2	3/16	230	11	3/16	16-18
	2 (rev)								
1/4	1	(b)	0-3/32	1/2	3/16	270	11	3/16	18-20
	2 (rev)*								
3/8	1	(b)	0-3/32	1/2-5/8	1/4	360	9	1/4	20
	2								
	3 (rev)*								
1/2	1	(b)	0-3/32	3/4	5/16	400	9	1/4	30
	2				5/16	480		1/4	30
	3 (rev)*				5/16	480		1/4	30

(a) Square butt. (b) 60/70° included angle. Single V preparation.

\* Reverse side back-chipped and last pass completed with addition of filler.

TABLE I A  
*Tungsten inert gas welding T-joint fillet welds.*

Thickness in	No. of passes	Dia. of cup in	Dia. of electrode in	Current amps.	Arc travel speed in/min.	Dia. of filler in	Argon flow cft/hr.	Remarks
1/16								Not recommended
5/64								Not recommended
3/32								Not recommended
1/8	2	3/8	1/8	180	9	1/8	12-14	One pass each side of joint
3/16	2	3/8	3/16	260	9	3/16	16-18	One pass each side of joint
1/4	2	1/2	1/4	310	8	3/16	18-20	One pass each side of joint
5/16	2	5/8	5/16	400	6	1/4	22-24	One pass each side of joint
3/8	2	5/8	5/16	475	6	1/4	30	One pass each side of joint
1/2	2	5/8	5/16	540	6	1/4	30	One pass each side of joint

1. For horizontal, vertical and overhead fillets, reduce welding current by approximately 20%.
2. Penetration into the root of fillet welds with the argon tungsten arc is difficult to obtain. This becomes more pronounced as the thickness increases. Care must be taken to prevent "bridging" the root during welding.

checked by tests, and subsequent workmanship kept to the same standard by frequent and capable inspection.

Table II gives typical average values for the breaking strength of tungsten inert gas arc welded aluminium joints and can be used as a guide in preliminary design.

TABLE II  
*Typical weld strength : Tungsten inert gas welded joints.*

Alloy	BSS	Typical ultimate tensile stress across full butt-weld (tons/sq in)	Typical ultimate shear stress across throat of longitudinal fillet weld (tons/sq in)
65 SWP		12	(8)
51 SWP	H 10	12	(8)
B 54 SM*	N 5/6	16	(8)
A 56 SM*	N 6	17	(8)
M 57 S	N 4	11	6
3 S	N 4	7	4
2 S	1 C	5½	3

\*These alloys comply with Lloyds Register of Shipping tentative requirements, but when welded will usually only meet this specification when permanent backing bars are used.

- Notes.—1. The throat of a fillet weld is 0.7 of the weld size provided the weld is not concave.
2. Figures for shear stress depend on the filler material used. Those in brackets are tentative values for fillers of NW21 or NW6 for H10 alloys and NW6 for NP5/6 and NS6 alloys.
  3. In calculating the strength of a fillet weld, allowance must be made for lower strength at the beginning and end of the weld bead.
  4. The strength of a transverse fillet weld can be expected to be somewhat greater per square inch than that of a longitudinal fillet weld, but figures are not available.

### Metal inert gas welding process

A logical development of the TIG process is the metal inert gas welding process. In this process the

tungsten electrode is replaced by the filler material in continuous wire form which has a chemical composition similar to the parent material to be welded. The arc is struck between the parent plate and this wire, usually 1/16" or 3/32" in diameter, which melts and is deposited in the weld seam. As the wire gets consumed it is fed into the molten pool by a motorised feed arrangement. The wire is surrounded by an inert gas such as argon which allows the welding to take place in an inert atmosphere.

The main features of this process are: (a) the high current densities which enable deep penetration and high speeds of welding to be achieved, (b) the self-adjusting characteristic of the arc which gives consistently good welds and (c) the stiff arc which enables positional welding to be done with the greatest ease.

It has been observed that metal transfer in the normal arc takes place in large globules. However, as the current density exceeds a critical value, about 45,000 to 50,000 amps/sq inch, the transfer suddenly changes from globular to spray type. In the latter, the transfer takes place as a fine spray (and can be directed vertically or overhead) which makes the arc at the same time stiff.

The change-over to spray type of transfer is supposed to be due mainly to the magnetic pinch effect. Other causes are also contributory such as expanding gases dissolved in the filler wire, and the plasma jet force produced by the constriction of the arc resulting from the use of thin wires. The magnetic pinch effect is produced by the magnetic force exerted on the wire by the passage of welding current. It is roughly equal

to  $\frac{I^2}{200}$  dynes where  $I$  represents the current density.

As the force increases proportionately to the square of the current density it is easily evident that this negligible force at low currents can become quite considerable when the current density is in the region of 50,000 amps/sq inch. This force helped by others disperses the globules formed into fine droplets and projects them forward as a fine spray.

The second characteristic of the metal inert gas (MIG) process is the self-adjustment that is achieved. This is a property inherent to the welding power source and needs some explanation.

The static volt/amp. characteristics of a normal power source for arc welding has a fairly steep drooping configuration. For MIG welding however, to obtain satisfactory self-adjustment, a flat or even a rising characteristic is preferred. This will be discussed later.

Even with a normal drooping characteristic of the volt/ampere curve a fair degree of self-adjustment can be obtained. In MIG welding the wire is fed at a pre-determined constant speed. The current is so selected that the arc establishes itself at a steady arc voltage of, say, 26 i.e. the burn-off rate of the wire is just equal to the feed-in rate at the current generated by the power source at a voltage of 26.

If due to some uneven movement of the operator's hand the arc suddenly shortens, the arc volts drop to, say, 24. At this voltage, because the power source has a drooping characteristic, the current increases considerably. The burn-off rate increases but the feed motor is feeding the wire as before at the same constant speed which is now less than the burn-off rate. The wire therefore burns faster than it is fed into the arc and the arc length automatically increases i.e. the arc voltage increases to the original stable point of 26. The converse happens if the arc voltage increases to, say, 28. Fig. 8 will make this point clear.

This self-adjusting characteristic helps the operator to maintain automatically a constant arc length which means welds of consistent quality.

The third characteristic is the stiffness of the arc which results from the spray type of metal transfer. This allows the arc to be pointed in any direction and facilitates positional welding. With this process it is fairly easy to weld in all positions.

Typical welding conditions are given in Tables III and III(A).

### More recent developments

Most of the recent developments in inert shielded arc processes have been confined to the MIG process. Developments have taken place in the power source, feeding units, techniques and shielding gases to expand the scope of the process.

While describing the self-adjusting characteristics mention was made that the flatter the volt/amp. characteristic the more the self-adjustment. A reference to Fig. 9 will show why this is so. A slight change in arc voltage, say, 4 volts results in a difference of only 20 amps with a steeper characteristic but results in a difference of 50 amps with a flatter characteristic. As the change in current determines the speed and extent of self-adjustment possible it is apparent that the flatter characteristic is better.

Extending the same argument, a level characteristic would give even better results. Therefore for MIG welding, constant potential power sources were developed. Here the current control is achieved by

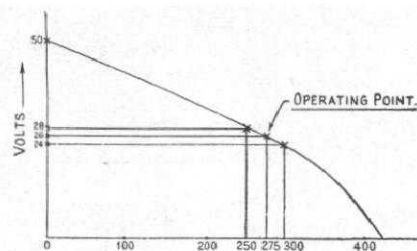


Fig. 8.

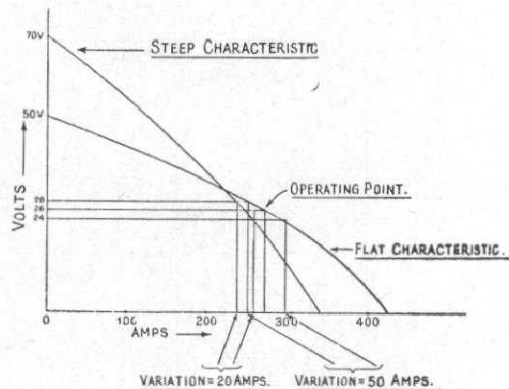


Fig. 9.

wire speed. Within a fairly wide range, the faster the speed the higher the current obtained with constant power sources.

As the arc itself has a rising characteristic attempts were then made to produce an ideal welding power source having a rising characteristic. This however was not an unqualified success because it is difficult to simulate the rising characteristic of the arc which depends on various variable factors, such as, the material or alloy being welded, the inert gas used, the wire diameter and, most important of all, the extension of the wire from the nozzle tip.

Constant potential power sources added to the popularity of welding of aluminium and its alloys and other light metals because they made it easier still to obtain consistently good welds with moderate skill.

Nevertheless, the field of this process was limited to materials  $\frac{1}{8}$ " or thicker as it was almost impossible to prevent a burn-through in thinner sections.

The main limitation was due to the size of the wire that could be used. The standard machines used "push through" type of wire feeders. The feeding unit had to push the wire after it was unrolled from the reel through about 10 to 15 feet of conduit to the gun. Thinner wires than  $\frac{3}{16}$ " were therefore found to be too soft to be fed through.

Recently "spool-on-gun" type of welding guns have been developed. A typical one weighs about 4 lb with the spool and the spool carries about 1 lb of aluminium wire. The wire feed motor and the gear reduction units are mounted on the gun itself so that the wire is pulled directly from the spool and pushed through only 6 inches to the arc. The gun is rated at

**TABLE III**  
*Metal inert gas welding: Flat butt welds with temporary backing.*

Thickness in	No. of passes	Edge Preparation	Root Opening in	Nose in	Dia. of filler in	Current amps	Arc travel speed in/min	Argon flow cft/hr	Remarks
1/8	1		3/64		1/16	160	36	50	
	2				1/16	160	36	50	
3/16	1		1/16	1/16	1/16	180	24	50	No back-chipping required.
	2				1/16	180	24	50	
1/4	1	40° included angle Single V	1/16	1/16	1/16	235	18	50	Back-chip after 1st weld to sound metal, then complete last pass.
	2				1/16	235	18	50	
5/16	1	40° included angle Single V	3/32	1/16	1/16	240	18	50	After 2nd pass back-chip and complete weld with last pass.
	2				1/16	240	18	50	
	3				1/16	240	18	50	
3/8	1	40° included angle Single V	1/8	1/16	1/16	240	12	50	After 2nd pass back-chip and complete weld with last pass.
	2				1/16	240	12	50	
	3				1/16	240	12	50	
1/2	1	40° included angle Single V	1/8	1/16	1/16	240	10	50	After 3rd pass back-chip and complete weld with last pass.
	2				1/16	240	10	50	
	3				1/16	240	10	50	
	4				1/16	240	10	50	

**TABLE III A**  
*Metal inert gas welding: Flat and horizontal fillet welds.*

Thickness in	No. of passes	Diameter of filler in	Current amps	Arc travel speed in/min	Argon flow cft/hr
3/16	1	1/16	235	24	50
1/4	1	1/16	245	16	50
5/16	1	1/16	245	14	50
3/8	1	1/16	245	11	50
1/2	1	1/16	250	11	50

about 200 amps and is meant to handle wires 0.030" to 0.040" at feed speeds of 100-900 inches per minute.

As the diameter of the wire could now be reduced to 0.030" the critical current required to obtain spray type of transfer was reduced and therefore thinner gauge aluminium could be welded. Further because the gun is a self-contained unit it can operate at any distance from the power source and therefore it can be used for welding awkward corners where accessibility is limited.

### Dip transfer

Another factor has contributed to the extension of semi-automatic arc welding to thinner sections and that is the recent development of the dip transfer technique otherwise known as the "short arc" process.

It was observed that below 200 amps an entirely different type of transfer to either globular or spray type described above can occur if the arc length was sufficiently short and the power source had certain special characteristics.

In this type of transfer the tip of the electrode actually dips into the pool of molten metal on the plate surface causing a short circuit of the power source of sufficient duration to extinguish the arc. This short circuit results in an increase in welding current which heats up the electrode tip so that it melts off and breaks and the arc is re-established. The process repeats itself rapidly.

It is evident that for the process to repeat itself rapidly the short circuit current must be sufficiently large and the build-up of such currents fast enough, i.e. the inductance of the power source must be low.



At the same time the inductance should not be so low that the response is too fast in which case a high peaked short circuit current builds up and the arc gets re-established with explosive violence blowing off the molten pool. Evidently the correct amount of inductance is necessary. To meet this condition new types of metal rectifiers have been built having a slightly drooping characteristic, the slope of which (the slope of volt/amp curve) can be controlled. A standard rectifier available has a controllable drooping characteristic ranging from 2 volts per 100 amps to 15 volts per 100 amps. The operator can therefore select the best volt/amp characteristic for a particular application.

It has been found that for the best welding performance a short circuiting cycle of 50-200 times per second is ideal. Such arcs are very short indeed (14-19 volts as against 22-28 volts for spray transfer). The arc force is so reduced that it is possible to tolerate fit-up gaps greater even than the plate thicknesses in certain cases and to weld exceptionally thin materials. Positional welding also becomes very much easier.

Thus with the gun mentioned above and 0.030" aluminium wires using dip transfer it is possible even for a welder of average skill to weld 1/16" aluminium in all positions. The welds may be produced very fast. For instance, it is possible to weld 16 swg aluminium at speeds in excess of 100 inches per minute and 10 swg up to 72 inches per minute.

### High current welding

Just as there was a limitation to the lower range of currents, MIG welding of aluminium could not be carried out with higher amperages. For instance, using aluminium wires 3/32" in diameter currents in excess of 400 amps produced extremely unsatisfactory welds. The weld pools were overagitated by the high arc forces and resulted in tunnelling, severe oxide folds and porosity. If this 400 amp limit could be exceeded it was apparent that it would be possible to weld heavy plates in fewer passes. Also the additional input of heat would tend to reduce the porosity because any porosity forming gas would have sufficient time to bubble out before freezing occurred.

Recently however by careful control of variables it has been possible to exceed this current limit and yet obtain satisfactory welds.

The welding torch should be able to pass 80 to 100 cft of argon without excessive turbulence. The welding wire must be free from foreign material. The edges of aluminium prepared for welding must be cleaned by removing the surface metal in which grease from the machining operations may have become embedded. Perhaps in the past too little attention was paid to the surface condition of the edge and the wire. An additional shield through which extra argon can be passed also helps to produce satisfactory welds.

Another important factor perhaps is the recent development of the slope controlled rectifiers as the power source which, as stated earlier, allows the operator to select the desired volt/amp characteristics

to suit the particular application. Whatever may have been the contributory factors it is well known now that high current welding can be done on aluminium, reducing the cost of welding not only because of the faster speeds possible but also because of the saving in edge preparation.

### Automatic and mechanised shielded arc welding processes

TIG and MIG welding can easily be adapted for mechanised welding. By mounting the respective hand welding torches on an electrically driven tractor it is possible to obtain extremely satisfactory mechanised welds for certain applications. For TIG welding an additional wire feed unit can be attached so that the filler wire is fed in by mechanised means. The arc length however will have to be controlled by the operator if there are undulations on the plate.

In mechanised MIG welding due to the self-adjusting characteristic the arc length is fairly constant but for really automatic control of arc length other means are made use of.

For TIG welding a servo-synchronous control drives a reversible motor which adjusts the height of the welding torch. The arc voltage which can be preset is compared with a reference voltage. The difference or the ERROR voltage is amplified and made to drive the height adjusting motor which either lifts the torch or lowers it until the "error" voltage is zero. The voltage can be maintained consistently constant. A filler wire attachment if desired completes the automatic welding set-up. The control described above is called the Automatic Arc Length Control and is achieved by electronic means.

For MIG welding the speed of the feed motor is generally controlled either by the arc voltage itself or by an electronic system which senses the arc voltage and drives the feed motor faster or slower so that the present arc length is maintained.

Automatic inert gas shielded welding eliminates the human factor from welding and makes it possible to obtain consistently good welds on aluminium and other metals.

### Inert gas shielded spot welding

#### MIG

This process was commercially introduced in 1954 for carbon steels and stainless steels but was not recommended for aluminium because of the difficulty in getting consistently good spot welds. The trouble was mainly due to the difficulty in getting a good start every time. Subsequent work has proved that for a given wire there is a voltage and current range within which reasonably good starting can be obtained. Table IV gives an approximate idea of these figures.

It is easier to obtain a weld when joining a thinner sheet to thicker material if welding can be done from the thinner side.



**TABLE IV**  
*Metal inert gas spot welding starting requirements.*

Aluminium alloy 1/16 in dia. filler wire (BSS)	Volt	Minimum current, amps.
GIC	25	180
	28	200
NG2I	24-27	130
NG5	24	360
	28	400
NG6	24	400
	28	250

MIG spot welding can also be used for plug welding of aluminium but is limited to a maximum of 3/16" thick material. This limitation is imposed by the tendency to develop cold laps at the bottom of plug holes. Even today the process is not very satisfactorily used for spot welding aluminium where high quality and consistency are the primary criteria.

### **TIG**

Tungsten inert gas spot welding of aluminium and other light metals have been to date not very satisfactory. Because high currents were required to melt the top plate and subsequently the bottom one, for welding aluminium, positive polarity on the electrode could not be used, while with D.C. negative polarity, the oxides, especially at the interface, did not get scavenged. Arc striking was comparatively easy.

Recently some development has taken place using D.C. negative polarity and clean, pickled sheets of aluminium, with high purity argon shielding and pointed thoriated tungsten electrodes. Under laboratory conditions consistently good welds have been produced but commercially the process has not yet been accepted.

### **Tungsten arc cutting and the plasma torch**

Ability to cut a metal easily plays an important part in fabrication work and therefore contributes to the ease of welding and in turn to the popularity of the metal concerned. Site cutting, bevelling and shaping aluminium are not as easy as on mild steel which is amenable to gas cutting.

Recently a great advance has been made in adapting plasma torches and tungsten arc cutting, which uses a form of this plasma torch, has been developed.

In this process an arc is struck between the tungsten electrode and the aluminium plate to be cut. The arc is constricted and made to pass through a water cooled narrow orifice. A shielding gas such as a mixture of argon/hydrogen (25-75%) or nitrogen/hydrogen (25-75%) is used. The arc, when constricted, produces a high temperature high velocity plasma jet. The

shielding gas is propelled forward at very great speeds and while the resulting temperature melts a narrow portion of the plate to be cut, the resulting kinetic energy of the plasma jet cuts the metal neatly by blowing away the molten metal. The surface produced is clean and free from oxides and dross. Speeds of cutting of 100-150" per minute are possible on 1/2" thick aluminium (250"/min on 1/4"; 30 to 50"/min on 4 1/2" thick plates).

This is a patented process and has not yet been introduced in India. Although machine cutting is preferred, hand cutting can also be done with a bit of skill. This process when it gets wider publicity and attains popularity, will surely prove a boon to the aluminium fabricator.

### **Titanium**

Titanium is a metal which has gained commercial importance in recent years. This is mainly due to its special properties such as its high strength, corrosion and heat resistance, etc., which are of prime importance in modern technology relating to rocket and jet powered engines.

The difficulty in welding titanium is due to its proneness to absorb oxygen, nitrogen and to some extent hydrogen from the welding atmosphere and get embrittled. Therefore the more common methods of fabrication such as gas or arc welding cannot be employed.

Spot welding can be done easily but for large fabrication work inert gas shielded arc processes are employed.

Both TIG and MIG welding can be used although the latter requires special wires. However TIG welding is the most popular in conjunction with D.C. power sources.

Tungsten inert gas (TIG) welding with a normal torch is unsatisfactory because the argon shielding from a normal shield is insufficient to protect the metal heated above the critical temperature both ahead and behind the molten pool. Therefore special shields having additional trailing and leading covers are employed. A larger area of the seam is thus protected and shielded during the period when it is hot enough to absorb oxygen and nitrogen from the atmosphere. To protect the underside, similarly, a backing groove which is flushed with pure argon is employed.

Where a titanium or its alloy component has to meet critical conditions even this method of welding is not quite satisfactory. Therefore special inert gas chambers are used for welding such items. A gloved compartment which can be evacuated is resorted to. Where evacuation is not possible flushing out for a fairly long period with pure argon can be done although the results obtained are not as satisfactory.

The articles to be welded are put inside the compartment which is then evacuated and flushed with pure argon. The operator standing outside, welds the material by putting his hands through the gloves. An observation window allows him to watch the pool and manipulate the torch and wire as desired.

Excellent welds in titanium are obtained by these

processes and the metal and its alloys are being increasingly employed where their special properties make them the best choice.

### Future developments

Atomic energy and nuclear power stations have recently made popular the use of light metals and their alloys. As stated in the beginning, the ease with which these could be welded, thanks to the recent developments in the field of inert gas shielded processes, has played a very important part in the popularity these metals and alloys have gained in the recent past.

Developments in regard to better and cheaper shielding gases or mixtures of shielding gases may be expected in the near future. Better and easier methods of fabrication may yet be developed such as, for instance, ultrasonic welding or electron beam welding which are at present in their infancy.

### Conclusion

In the foregoing paragraphs an attempt has been made to outline briefly the recent developments in the field of joining light metals and alloys. Although the details are not necessarily complete it is hoped that a fairly comprehensive survey has been effected.

### Acknowledgements

The writer is indebted to various magazines on welding for some of the information and data contained in this paper. He takes this opportunity to acknowledge these with thanks. He also thanks his colleagues for the help they have rendered in editing this paper.

Finally, he thanks the Directors of Indian Oxygen Company Ltd. and the organisers of this Symposium for allowing him this opportunity to present this paper.

## DISCUSSIONS

*Mr. S. C. Bhalla, NML:* I would like to know if it is possible to use a cheaper gas, such as  $\text{CO}_2$ , instead of helium or argon for TIG welding.

*Mr. J. A. Muliyl (Author):* In tungsten arc process, a completely chemically non-reactive gas has to be employed, the principle being to exclude  $\text{N}_2$  and  $\text{O}_2$  from the welding zone. There are several other inert gases no doubt. But carbon dioxide is a highly reactive gas at the arc temperature and dissociates into carbon monoxide and oxygen in the arc; the oxygen combines with metals such as aluminium to form oxides, which is very undesirable. Nitrogen is one of the gases which can be used for welding copper but unfortunately even nitrogen is not good enough for aluminium, the reason being that nitrogen being a diatomic gas, dissociates into atomic state at the arc temperature and becomes highly reactive and forms nitrides with aluminium. However, for welding copper, nitrogen has been found useful. There are other rare gases like Kr, Xe, Ne. It can be naturally expected that these gases are equally effective but they are available in such small quantities that it would not be economical or commercially possible to use them.

*Mr. U. P. Mullick, Institution of Consulting Engineers, Calcutta:* I would request the author to give a comparative cost data for using welding per ft run by gas welding, resistance welding and plasma torch method as well as the cost of electrodes regarding light metal welding.

*Mr. J. A. Muliyl (Author):* I have not worked out

the cost figures but it is a well known fact that resistance welding is the cheapest as far as running costs are concerned as the cost comprises only labour and electrical energy consumed. However, the capital outlay involved in installing an electrical resistance welding machine of the complicated type required for welding of aluminium is considerable and depreciation alone will form a large percentage of total costs. Cost of welding of aluminium by gas and argon arc processes, depends to a large extent on the availability of materials in India. Even in other countries where argon gas and the necessary equipment are readily available, the cost of welding of aluminium by the argon arc process is not as cheap as by gas welding. This is more pronounced in India where gas welding is already popular while the argon arc equipment and, till recently, even argon had to be imported.

But as I have already said there are limitations to welding of aluminium by gas and it is not possible to use corner or fillet welds. This naturally imposes several limitations on the designers. Many fabricators, therefore, prefer to pay a little higher for argon arc welding and use that process for joining aluminium.

In view of the foregoing, I estimate that in India the costs of argon arc welding will work out to  $1\frac{1}{2}$  times the cost of gas welding.

*Mr. R. Choubey, NML:* I would like the author to give the relative advantages of the tungsten electrode process in the inert arc welding processes.

*Mr. Muliyl (Author):* The two processes are complementary to each other. Till recently before the Fine Wire arc welding process was developed, there was definite demarcation of thicknesses that could be welded with the two processes. Inert gas metal arc process, due to its high current densities, naturally could not be used for gauge materials. Therefore it was restricted to thicknesses of 3/16" and over. Tungsten arc process was used for welding of thin sheets as one can use 20 amps or even lesser currents. This is the main difference. Where it is possible to use both processes, there are, of course, many advantages in using metal inert gas welding, compared to tungsten inert gas welding since metal inert gas welding is much faster and cheaper and easier to operate. With the advent of the fine wire welding process, the inert gas metal arc welding process is gaining further in popularity as it enables gauge thicknesses also to be welded in all positions.

*Mr. S. C. Bhalla, NML:* I would request Mr. Shankar to let us know how the weldability of light alloys are determined and also of the various problems encountered in welding in Hindustan Aircraft Ltd.

*Mr. U. P. Mullick, Institution of Consulting Engineers, Calcutta:* Mr. Shankar may also let us know the details of testing the welded joints in regard to tensile, compression and torsion strengths for plain sheet and lump piece welds; and whether any chart or tables are followed or each welded joint is tested by practical strain tests.

*Mr. P. K. Chatterjee, T.D.E. (Vehicles and Engg.), Ahmedabad:* As the HAL are the largest users of the light alloys of the heat-treatable type, viz. the copper-bearing duralumin, Cu-Mg-Si alloys of the conventional composition and also the Zn-bearing alloys, which they use to quite a large extent, I would like to know whether they are welding them, and if so, what special difficulties they are finding.

As Mr. Bhalla desired, I would also like to know whether Mr. Shankar could give us some method of assessing a term which goes by the name of weldability and eludes all evaluation. For example, there is a general rough test "Reeds-cracking test" for steel. For aluminium alloys, how could one assess and evaluate the term "weldability".

*Mr. M. B. Shankar, Hindustan Aircraft Ltd., Bangalore:* Welding is a means of jointing metal parts or components which may be of same material composition or of different shapes or as lately of dissimilar compositions. "Weldability" of light alloys is principally determined by their compositional characteristics which in turn determine the non-heat treatability or otherwise of the alloy. Most simply mentioned, the ultimate strength and soundness of the welded structure is a measure of weldability. The design features and the extent of previous hot or cold working also determine the suitability or otherwise of welding. Wrought products of the duralumin type of alloys (Al-Cu-Mg-Si) and the higher strength (Al-Zn-Mg) alloys used for long range aircrafts, are not recommended for welding. Also, even spot welding of duralumin type (24 ST) alloys is not recommended where corro-

sive conditions are encountered in service. Only non-heat treatable alloys are chosen for welding for satisfactory service. As far as possible, no welding is considered in case of heat treatable alloys due to uncertainties in obtaining uniformity of the structural constituents and strength continuity with the parent metal. However, some heat treatable alloys, at the hands of expert welders and with adequate precautions can be welded with post-weld heat-treatment as imperative.

All types of welding are undertaken at HAL. They are universally adopted for jet engine assemblies and to a very limited extent for aircraft skins (wings, tail units and fuselage). Lately in modern supersonic aircraft where light alloys are unusable, stainless steel skins and major assemblies are of welded construction.

In general, welding is of the distinct types, namely, (1) fusion and (2) pressure or forge. In fusion welding, the method of heating is either by (a) gas, (b) electric arc or (c) chemical action (thermit).

In gas welding, oxy-acetylene or atomic hydrogen is used. To protect against any oxidising tendencies, in the former case fluxes for welding are usually employed. The precautions to be taken in such cases are: (1) cleanliness of faying surfaces, (2) freedom from adherent oxide coatings, and (3) careful removal of fluxes or slags after welding, as, otherwise, their presence would induce corrosion. In electric arc welding, tungsten or carbon rods as electrodes shielded by argon or atomic hydrogen, are used with filler metals. Pressure welding with electric resistance is another major group, embracing spot seam, projection and flash-butt weldings.

The general defects that arise from welding are: cracks (peripheral or internal), cavities, porosity overlap, inclusions, metal expulsions, incorrect weld size, misalignment, inadequate penetration and fusion, under-cutting, surface burns, warpage, etc. There are numerous difficult problems in welding which daily arise in jet engine construction in HAL, which are overcome also in collaboration with the representatives of reputed firms like Rolls Royce, Bristols and Folland.

The modern trend is towards replacement of welded assemblies by integrated (forged and elaborately machined) parts as critical components of the aircraft (such as spares, booms, etc.) with a view to eliminate the uncertainties and defects associated with welding.

Mechanical tests, micro-examination and non-destructive (radiographic or ultrasonic) testing are carried out on welded assemblies. As mostly welding of light alloys is confined to sheet or plate products, samples are tested for tensile properties. The nature and location of fractures tell the story of the weld. The fractures through the weld or in the fusion zone are indicative of defective welding. Further, discontinuity of weld structures, grain coarsening or burning effects, oxide inclusions, cracks, lack of penetration, etc. are revealed in the micro-examination of welds and adjacent areas. Non-destructive testing methods throw light on the internal soundness of the weld. Welded assemblies for critical parts for aircraft or jet



engine are tested under alternating stresses (Fatigue properties), simulating service conditions or for creep properties.

Strictly no weld-defects are tolerated. But in production small defects are inevitable and as costly man-hours cannot easily be set aside, welds are accepted with so-called "permissible" defects. In the aircraft industry no compromises are allowed nor sought. The tolerance of "permissible" defects may lead to wrong connotation and misjudgement by inexperienced hands. It is advisable, therefore, to have the parts showing even small defects, as far as possible, reworked. Reverting a little to the so-called "permissible"

defects, I may state that peripheral cracks are more harmful than internal cracks in welded parts subjected to dynamic stresses. A number of pin holes wide apart may be harmless but a few close ones in a line are dangerous.

As to the question of welding of "lumpy" parts, I may repeat that it is always advisable to prepare the faying surfaces as geometrical faces prior to welding. Usually, welding is not resorted to in joining "lumps". Perhaps, the question pertains to salvaging of castings with slight defects corrected by welding. The repaired castings or fabricated parts are, invariably, radiographed for assurance of the soundness of the weld.

